WILD CABLES IN FUSION PLASMAS (THEORETICAL VIEW)

A.B. Kukushkin, V.A. Rantsev-Kartinov INF RRC "Kurchatov Institute", Moscow 123182 Russia kuka@nfi.kiae.ru

1. Introduction.

Our previous studies of long-living filaments (LLFs) in various laboratory plasmas, namely gaseous Z-pinches [1,2(b),3,4,5(a)], plasma foci [7], laser-produced plasmas [4], tokamaks [2(c),5(b),6], and cosmic space [1,2(a),3,4,5(a)], has lead us to the conclusion [3,4,5(a),8] that only the quantum (namely, molecular) long-range bonds inside LLFs may be responsible for their observed unbelievably high mechanical stability and survivability, rather than the mechanisms of a classical particles plasma. Specifically, the carbon nanotubes have been proposed [3,4,5(a),8] to be the major microscopic building blocks of the respective microsolid component of LLFs because such nanotubes are known to be produced in various *low-temperature* electric discharges and might be assembled during electric breakdown from individual carbon nanotubes by the originating/passing electric current to give self-similar tubules of macroscopic size.

In the present paper, we give short description of previous and just formulated hypotheses suggested for interpreting the observations of the tubular rigid-body LLFs of macroscopic size in tokamak and Z-pinch plasmas, including recent observations [9(a)] (for details, see also preceding paper in this conference proceedings). Here, major stress is made on suggesting a qualitative model for the survivability of hypothetical microsolid skeletons of LLFs in *high-temperature* plasmas (see also [9(b)]).

2. Microsolid skeletons of long-living filaments in plasmas: hypothetical life story.

The mechanism of survivability of microsolid skeletons in hot plasmas naturally stems from the proposed below mechanism of the nonlocal transport of energy from external electric circuit to plasma core. In this section we give very short description of the formation and survivability of skeletons, which is based on the picture of electrical breakdown suggested in [8] and on the possibility of transporting the EM energy along/inside the LLFs suggested in [6].

The major elements of the scheme for particular case of tokamak plasmas are as follows.

- (i) A deposit of carbon nanotubes, of the relevant quantity, is produced at the inner surface of the chamber during discharge training, from either graphite-containing construction elements (like, e.g. limiters or walls) or carbon films produced by the deposition of the organic oils normally used in the vacuum pumping systems (the nanotubes may be formed due to rolling up of monolayers ablated from solid surfaces or thin films).
- (ii) Electrical breakdown occurs along chamber's surface (or its part, namely, the inner side of the torus) and is based on the substantially enhanced rate of (cold) autoemission and thermoelectric emission of electrons by the nanotube (as compared to macroscopic needles).
- (iii) The microsolid skeletons are assembled from individual nanotubes which are attracted and welded to each other by the passing electric current to produce self-similar tubules [4,8] of macroscopic size, of centimeter length scale and larger (this electric current is produced by the poloidal magnetic field B_{pol} pumped from the external circuit into the chamber).
- (iv) Once the skeleton (or its relevant portion) is assembled, the substantial part of the incoming $B_{\rm pol}$ brakes at it and produces a cold heterogeneous electric current sheath which is made of conventional plasma. A part of $B_{\rm pol}$ near the skeleton is bouncing along its every rectilinear section (i.e. between the closest points of the deviation, even small enough, from rectilinearity). This produces a high-frequency EM wave which, in turn, produces, by the force of the high-frequency (HF) pressure [10] (sometimes called in literature the Miller force), the cylindrical cavities of a depleted electron density (primary channels) around the skeletons.

(v) At the plasma column's edge the bouncing boundary of the cavity from the scrape-off layer side produces a HF valve for the incoming B_{pol} , because of the node of the standing wave at the edge. This works as a HF convertor of a part of the incoming B_{pol} which is transported then along the skeleton in the form of EM waves. (Besides, a part of B_{pol} which reaches the cavity in the conventional regime of the diffusion of B_{pol} , is transformed into a HF field by the oscillating boundary of the cavity). These waves sustain the cavity and protect the skeletons from direct access of thermal plasma particles. Therefore the skeleton appears to be an inner wire of the cable network (a *wild cable* network) in which the role of a screening conductor is played by the ambient plasma.

In this paper we restrict ourselves to quantifying the above picture in its quasi-stationary stage of energy inflow through the wild cable network.

3. A mechanism of survivability of microsolid skeletons in hot plasmas.

The individual wild cable is formed by a microsolid tubule, of length L_c , which plays the role of an inner wire of radius r_w . Significantly, the channel for transporting the EM energy is formed by the EM waves themselves so that each inner wire is embedded into its own cylindrical almost-vacuum cavity of effective radius r_c in a plasma of electron and ion temperatures T_e and T_i , respectively.

We consider the frequency of EM wave which propagates in the individual cable to be determined by the geometry of the cavity rather than by the eigenmodes of ambient plasma. The latter requires large enough internal reflection of the EM wave inside the cavity (as in a resonator) so that substantial part of the EM energy is trapped in the individual cavity and possesses, in its major harmonic ω_C , a narrow spectral distribution (ω_p is plasma frequency, c, the speed of light):

$$\mathbf{W}_{c} \approx \frac{\mathbf{p}c}{L_{c}} < \mathbf{W}_{pe} . \tag{1}$$

For tokamak geometry, one has the following chain of transformations of EM waves. The cavities at plasma edge (they normally possess some declination with respect to the boundary magnetic surface) allow the field lines of B_{pol} to move directly inside the cavity and thus produce the magnetic (H) wave. For the strongest EM wave among H waves, the H_{11} wave, one has:

$$1 \approx 2L_c > 1_{crit} \sim \alpha r_c$$

where λ_{crit} is the critical wavelength for free propagation of the respective EM wave in the cable; for H_{11} wave one has

$$a_{H_{ij}} \sim p$$
.

Therefore, the trapping of H_{11} wave in the edge cavity leads to wiring of magnetic field lines round the inner wire that produces TEM and electric (E) waves propagating in both directions (the strongest wave among E-waves will be E_{01} wave). However, the E_{01} wave will also be trapped in the cavity, because of

$$a_{E_{0.1}} \approx 2.6$$

in contrast to TEM wave, because of

$$I_{crit}^{TEM} = infinity.$$

Also, the H and E-waves, in contrast to TEM wave, are detached from the wall (in radial direction, these waves are the standing ones) so that only the TEM wave can actually maintain the boundary of the cavity. Thus, the edge cable converts a part of B_{pol} into HF TEM wave propagating inward. The signs of this HF field may be found in the measurements of EM fields outside plasma column because a small part of this field is reflected outward, into the gap between the plasma and the chamber (see below).

It is assumed also that the presence of an external strong magnetic field of a (very) low oscillation eigenfrequency (or inverse characteristic time) ω_{B0} ($\omega_{B0} << \omega_{C}$) doesn't influence substantially the form of the cavity, even in the case when $\omega_{C} << \omega_{Be}$ (ω_{Be} is electron

gyrofrequency): the latter requires the amplitude \mathbf{E}_0 of the HF electric field of the major harmonic to have a non-zero component parallel to magnetic field (in that case we will assign \mathbf{E}_0 to the respective component of the amplitude).

The distribution of plasma density around the inner wire can be described by a set of equations for the two-temperature quasi-hydrodynamics of a plasma in a HF EM field [11], with allowing for the positive electric charge of the inner wire (cf. item (ii) in Sec. 2).

Under condition $l_E >> r_D$, where l_E is the characteristic length of spatial profile of $\mathbf{E}_0(\mathbf{r})$ and r_D is Debye radius, one can neglect the deviation from the quasi-neutrality and arrive at quasi-Boltzmann distribution (see e.g. [11(b)]):

$$n_e = n_{e0} \exp(-\frac{\Psi}{T_e + T_i}), \quad \Psi = \frac{e^2 E_0^2}{4m_e \omega_c^2},$$
 (2)

where n_{e0} is background density of plasma electrons.

We start our analysis with obeying the condition for the detachment of electrons:

$$eU_0 > 2p\frac{r_c}{L_c}\sqrt{Am_ec^2(T_e + T_i)}, \quad A \sim \frac{r_w^2}{r_c^2}\ln(\frac{n_{e0}}{n_{e\min}}),$$
 (3)

where U_0 is the effective voltage bias of the TEM wave in the cable ($\mathbf{E}_0(\mathbf{r}) \sim U_0/r$, and r is the radial coordinate in a circular cylindrical cable), n_{emin} is the minimal density permitted, at a temperature T_e , for the inner wire to be not destroyed by the plasma impact. For tokamak case ($n_{e0} \sim 10^{13} \text{ cm}^{-3}$), we take A ~ 5 .

Equation (3) is to be coupled to the condition of the applicability of the concept of the (- $?\Psi$) force, $\rho << l_E$ (ρ is the amplitude of electron's oscillations in the HF electric field), which limits the eigenfrequency ω_C from the side of low values. For our estimates, this limitation, however, may be weakened so that it takes the form:

$$eU_0 < \mathbf{p}^2 m_e c^2 \frac{r_c (r_c - r_w)}{L_c^2}, \tag{4}$$

The following limitation, for the aspect ratio of the vacuum channel of the cable, follows from Eqs.(3),(4):

$$\frac{r_c - r_w}{L_c} > \frac{2}{\boldsymbol{p}} \sqrt{\frac{A(T_e + T_i)}{m_e c^2}}.$$
 (5)

And finally, the HF electric field in the cables may be related to the observable turbulent electric fields. Indeed, the wild cables are the strong sources of electrostatic oscillations in plasma, first of all in the direction along the strong magnetic field. The presence of a strong turbulence should be compatible with the presence of wild cables (i.e. there should be a sort of the feedback between plasma and cavity): one may consider the cable's cavity as a soliton with such a strong reduction of the eigenfrequency (a redshift) that soliton's velocity becomes independent from dispersion. For

$$\frac{W}{nT}$$
 < 1, $W = E_0^2 / 16 \boldsymbol{p}$,

this gives the following rough estimate

$$\frac{W}{nT} \sim (1 - \frac{\omega_c}{\omega_{pe}}). \tag{6}$$

At the quasi-stationary stage of discharge, one may evaluate the patial distribution of the amplitude E_{turb} of the turbulent electric field, regardless of its spectral distribution, as described, in radial direction with respect to the individual cable, by the scaling of the TEM wave. For the contribution of a single cable, one has:

$$E_{turb}(r) \sim \frac{U_0}{r}. (7)$$

Equations (1),(3) and (4), along with rough estimates of Eqs.(6) and (7), establish a set of equations that enable one to evaluate the plausibility of the presence of wild cables in tokamak plasmas, using available data on measuring the values of ω_C [12] (and/or L_C) and E_{turb} [13].

Now we can test the problem for typical data from the periphery of the T-10 tokamak, keeping in mind the closeness of T-10 regimes analyzed in [12,13] and those for the experimental data analyzed in [9(a)].

First, the spectra of the HF EM field in the gap between the plasma column and the chamber in the GHz frequency range were measured in [12]. They revealed a distinct bump at $v_C \sim (4-5)~10^9$ Hz, of the width $\sim 2~10^9$ Hz, which always exists in ohmic heating regimes and increases with electron cyclotron heating (this bump is a stable formation and it moves to the lower frequencies and turns into a peak only under condition of strong instabilities, especially disruption instability). This gives $L_C \approx 3$ cm. Note that this is in reasonable agreement with the data of Fig. 5 in [9(a)] (see also this conference proceedings, Fig. 6 of the preceding paper) where $L_C \approx 4-5$ cm.

Second, the analysis of observations of Stark broadening of deuterium spectral lines (and their polarization state) at the periphery of the T-10 tokamak in the region of $T_e \sim 100$ eV, allowed [13] to estimate the spectral range of HF electric fields ($\omega \approx \omega_{pe} \sim 10^{11}$ Hz), their amplitude (E ~ 10-20 kV/cm) and angular distribution.

For $L_C = 3$ cm, $T_e = 100$ eV, Eq. (5) gives a constraint

$$S = \frac{r_c - r_w}{L_c} > 0.03.$$

For $(r_C-r_W) \sim r_C$, from Eq. (3), one can find the absolute minimum of voltage bias: $(U_0)_{min} \approx 5$ kV. For S=0.03, Eqs. (3) and (4) give $U_0 \approx 5$ kV, while for S=0.1 one has $15 < U_0(kV) < 50$. Further, Eq. (6) gives $E_0(r_C) > 50$ kV/cm, while, for $r_C \sim 1-2$ mm and $< r > \sim 1-3$ cm (< r > is the average distance between individual cables in the region of observation), Eq. (7) gives the estimate $E_0(r_C) > 10^2$ kV/cm, or $U_0 > 10$ kV. It follows from the results of numerical solution of the Poisson equation that, e.g., for $U_0 \sim 30$ kV at the distance $r \sim 2$ mm the effective electron density falls down, with respect to its background value, at least by seven orders of magnitude.

The values of E_0 on the inner wire ($r_{wire} \sim 1$ mm) require anomalously low consumption of EM energy by the wire. The assumption [9] of an anomalously low dissipation of EM energy in such skeletons seems to be supported by the very recent observations [14] of *persistent electric currents* in the fragments of the *non-processed* (i.e. *wild* !) deposits containing the multiwall carbon nanotubes.

4. Conclusions.

The analyses of experimental data from various well-done plasmas suggest that plasmas with *long-living* filaments is such a form of the fourth state of matter, which is an intricate mixture of three other states: namely, gaseous (plasma particles), liquid (magnetic field which is frozen, at least, in plasma electrons) and solid.

Recall that just the presence of the inner wire (namely, microsolid skeleton with electrically conducting blocks) in the wild cable is repsonsible not only for the observed anomalous mechanical stability of this structure but for the formation of TEM waves in the cavity that is nedeed for the self-sustainment of the cavity and for the transport of EM energy to plasma core.

It follows from the above that wild cables could be:

- (i) a strong candidate for the nonlocal (non-difusion) component of heat transport (and observed phenomena of fast nonlocal responses) in tokamaks;
 - (ii) a powerful source of non-linear waves and (strong) turbulence throughout plasma volume;
- (iii) a low-dissipation waveguide responsible only for the spatial profile of poloidal magnetic field in tokamaks, rather than total resistance of plasma (in agreement with the observed applicability of Spitzer, or close, resistivity to describing the ohmic heat release);
- (iv) a universal phenomenon in well-done laboratory plasmas and space; in particular, similar wild cables may form in gaseous and wire-array Z-pinches and be responsible for the fast nonlocal transport of EM energy toward Z-pinch axis.

Acknowledgments. The authors appreciate discussions of the paper with V.V. Alikaev, Yu.A. Danilov, A.G. Frank, Yu.L. Klimontovich, V.M. Leonov, S.V. Mirnov, V.I. Poznyak, K.A. Razumova, A.A. Rukhadze, I.B. Semenov, V.D. Shafranov, V.P. Silin, and V.L. Vdovin, and participants of seminars in the Kurchatov Institute, Lomonosov Moscow State University, General Physics Institute RAS, and Lebedev Physical Institute RAS. Our special thanks to V.I. Kogan for his support and encouragement.

REFERENCES

- [1]-[6], [8], and [9]: Kukushkin A.B., Rantsev-Kartinov V.A.:
- [1] Laser and Part. Beams, 16 (1998) 445.
- [2] Rev. Sci. Instrum., (a) **70** (1999) 1387; (b) Ibid, p. 1421; (c) Ibid., p. 1392.
- [3] Proc. 17th IAEA Fusion Energy Conf., Yokohama, Japan, October 1998, IFP/17.
- [4] Proc. 3rd Symposium "Current Trends in Int. Fusion Research: Review and Assessment", Washington D.C., March 1999, Ed. E.Panarella, NRC Research Press, Ottawa, Canada (to appear), 33 pp.
- [5] Proc. 26-th Eur. Phys. Soc. conf. on Plasma Phys. and Contr.Fusion, Maastricht, Netherlands, June 1999, (a) p. 873 (http://epsppd.epfl.ch/cross/p2087.htm), (b) p. 1737 (p4096.htm)
- [6] Preprint of Kurchatov Institute, IAE 6095/6, Moscow, May 1998, 48 pp.
- [7] Kukushkin A.B., Rantsev-Kartinov V.A., Terentiev A.R., Fusion Technology, **32** (1997) 83; Kukushkin A.B., Rantsev-Kartinov V.A., Terentiev A.R., Cherepanov K.V., AIP Conference Proceedings vol. 409, Dense Z-pinches 4th Int. Conf., Vancouver, Canada, May 1997, Eds. N.R.Pereira, J.Davis, and P.E.Pulsifer, AIP Press, New York (1997), p. 381.
- [8] Preprint of Kurchatov Institute, IAE 6111/6, Moscow, October 1998, 32 pp.
- [9] (a) Preprint of Kurchatov Institute, IAE 6157/6, Moscow, October, 1999, 20 pp.; (b) "arXiv.org e-Print Archive", http://xxx.lanl.gov/abs/physics/9910048.htm.
- [10] Gaponov A.V., Miller M.A., Zh. Exp. Teor. Fiz. (Sov. Phys. JETP), **34** (1958) 242; Volkov T.F., In: Plasma Physics and the Problem of Controlled Thermonuclear Reaction, Ed. M.A. Leontovich, [In Rus.], USSR Acad.Sci., 1958, Vol. 3, p. 336, Vol. 4, p. 98; Sagdeev R.Z., Ibid., Vol.3, p. 346.
- [11] (a) Gorbunov L.M., Uspekhi Fiz. Nauk (Sov. Phys. Uspekhi), **109** (1973) 631; (b) Litvak A.G., In: Voprosy Teorii Plazmy (Reviews of Plasma Phys.), Eds. M.A. Leontovich and B.B. Kadomtsev, [In Rus.], vol. 10, p. 164.
- [12] Poznyak V.I., et. al. Proc. 1998 ICPP and 25-th Eur. Phys. Soc. Conf. on Plasma Phys. and Contr. Fusion, 1998, Prague, ECA Vol. 22C (1998) p. 607.
- [13] Rantsev-Kartinov V.A., Fizika Plazmy (Sov. J. Plasma Phys), **14** (1987) 387; Gavrilenko V.P., Oks E.A., Rantsev-Kartinov V.A., Pis'ma Zh. Exp. Teor. Fiz. (JETP Lett.), **44** (1987) 315.
- [14] V.I.Tsebro, O.E.Omel'yanovsky, A.P.Moravsky, Pis'ma ZhETF (JETP Lett.), 70 (1999) 457.